Snowmass2021 - Letter of Interest

Dark Matter and Early Universe Physics from Measurements below the Galaxy Formation Threshold

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*
■ (TF08) BSM Model Building
■ (TF09) Astro-particle physics & cosmology
■ (CompF2) Theoretical Calculations and Simulation

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Abstract: (must fit on this page)

The distribution of dark matter on extremely small physical scales, well below the threshold of galaxy formation, is a largely unexplored frontier in observational cosmology. These physical scales are the most sensitive to any non-gravitational interactions in the dark sector. In models of inflation, small-scale modes were inside the horizon since the earliest times, and therefore bear signatures from early universe physics. Measurements of the abundance, mass profiles, and clustering of extremely low-mass and baryon-free dark matter structures ($M_{\rm halo} \ll 10^7 M_{\odot}; k \gg 100 h\,{\rm Mpc}^{-1}$) would provide unique, qualitatively new insights on the physical mechanism of inflation and the fundamental nature of dark matter. Several observational techniques based on gravitational lensing and stellar dynamics have been proposed that would exploit the survey capabilities and enhanced precision of cosmology/astrophysics experiments planned for the next decade (e.g., astrometric, photometric, and radial velocity surveys; gravitational wave interferometers and pulsar timing arrays). Collectively, these experiments would probe extremely small dark matter structures in Galactic and extragalactic environments, and are complementary in terms of sensitivity to varying dark matter density profiles. Some near-future experimental configurations could have sensitivity even to typical dark matter halos predicted in collisionless cold dark matter models, and greater sensitivity to more concentrated profiles (e.g., primordial black holes, ultra-compact minihalos, axion miniclusters). We advocate for increased theoretical and instrumentation efforts to develop these ambitious techniques, with a vision towards a future experiment to explore dark matter microphysics and the source of primordial density fluctuations through their signatures at extremely small scales.

The standard cosmological paradigm with (1) nearly scale-invariant adiabatic primordial density fluctuations and (2) collisionless cold dark matter (CDM) predicts that dark matter is clustered into halos with a nearly scale-invariant mass spectrum extending from massive galaxy clusters ($10^{15} M_\odot$) down to planet-scale masses. If the dark matter is composed of canonical weakly interacting massive particles (WIMPs) with mass $\sim$ 100 GeV, the minimum halo mass set by the free-streaming length is $\sim 10^{-6} M_\odot$ [21]. This simple model has proved adequate to explain observations from large-scale structure, down to the least luminous galaxies that reside in halos of $\sim 10^8 M_\odot$ [25,28,34,36]. Over the next 5-10 years, observations of ultra-faint galaxies, galaxy-galaxy strong lensing, stellar stream perturbations, and 21cm tomography will all probe dark matter halos that are small enough ($10^6 - 10^8 M_\odot$) to contain few if any stars.

Robust identification of dark matter structures well below the threshold of galaxy formation is a qualitatively new observational frontier that is currently mostly unexplored. Measurements in this regime are generically sensitive to a wide range of models that predict damped structure (e.g., warm dark matter, baryon/photon/neutrino scattering dark matter, decaying dark matter[39,47], late-forming dark matter[1], fuzzy dark matter[23,24], self-interacting dark matter, late kinetic decoupling of dark matter[7,8], multi-field inflation[48]) or enhanced structure (e.g., axion-like dark matter[2,9,22,29,46], inflationary models that produce vector bosons[20], cosmologies with early dark matter domination[4–6,17,18,35,49]) relative to CDM. Below, we highlight several proposed experimental approaches that could achieve sensitivity to stellar-and planet-mass-scale extended dark matter structures, by detecting their gravitational influence on a variety of observables.

Techniques to Probe Dark Matter and Early Universe Physics using Extremely Small Scales

• *Cluster Caustics:* Gravitational lensing by galaxy clusters produces caustics in which background objects are magnified by orders of magnitude, and the properties of the images provide a sensitive probe of the mass distribution in the lenses. Observations of background galaxies crossing through such caustics have already been employed to constrain the fraction of DM in compact objects[37], and similar techniques may be used to probe DM substructure. In particular, if the mass distribution of the lens is smooth, images appear in symmetric pairs across critical curves. Thus, asymmetries between these images probe inhomogeneities in the lens, and with detailed modeling, such asymmetries can be related to the abundance of substructure.

Analysis of asymmetries in the caustic-crossing arc SGAS J122651.3+215220 suggests that they are best accounted for by DM subhalos of mass 10^6–$10^8 M_\odot$ [14]. The same technique may be sensitive to lower masses as well: abundant light substructures should often be found very close to the critical curve, where they can produce a significant asymmetry in the images of sufficiently compact sources. The Vera C. Rubin Observatory will detect many more such cluster caustic lens systems.

• *Gravitational Microlensing:* Gravitational lensing due to the transit of a compact dark matter object near the line of sight to a source star may give rise to one or several lensed images with an enhanced total apparent luminosity. By convention, a microlensing event is defined by a fractional magnification of $\mu = 1.34$. From the non-observation of microlensing events, constraints can be derived on compact dark structures, a technique mostly studied for primordial black holes. Recently, such constraints have generalized to extended dark matter structures, such as subhalos, boson stars, and axion miniclusters[12,13,19]. The sensitivity to extended objects depends on their mass profile, with stronger constraints existing for more sharply peaked profiles. Current constraints exist for substructures as large as $10^3\,\mathrm{R}_\odot$ or about 10 AU for subhalos of $10^{-2} - 10^1 \mathrm{M}_\odot$ [13], and reach down to $10^{-11} \mathrm{M}_\odot$ for smaller structures. CDM subhalos would have radii of $\sim$pc in this range and are thus currently unconstrained through this probe.

Importantly, the sensitivity of microlensing experiments depends strongly on total observation time and cadence. Longer cadences provide greater sensitivity to more massive objects, and increased observation time increases the overall sensitivity of the survey. Dedicated microlensing studies could also take specific dark matter profiles into account, which typically lead to modified light curves in events.

• *Precision Astrometry:* Galactic subhalos can induce detectable proper motions in luminous background sources (*e.g.*, stars and QSOs) due to gravitational lensing[31,32,45]. Several methods have been identified to extract this signal with the ultimate goal of characterizing the lensing subhalo population, *e.g.*, identification of proper motion outliers due to lensing by compact objects, the use of matched filters to identify extended subhalos from locally correlated proper motions[32,45], and the spectral decomposition of the astrometric velocity and acceleration fields over large regions of the sky[31]. A proof-of-principle analysis using the matched filter approach and data from *Gaia* DR2 was recently presented[32], demonstrating sensitivity to $\sim 10^8 M_\odot$ subhalos extended at the $\sim$pc level—much less dense than what established methods relying on photometric microlensing are typically sensitive to. The different proposed methods are complementary and, taken together, will be able to probe a wide variety of scenarios—from NFW subhalos down to $\sim 10^6 M_\odot$ to populations of compact objects—when applied to future astrometric datasets such as those from the proposed space-based ESA *Theia* mission[44], the upcoming NASA Nancy Grace Roman Space telescope, and radio observations from Square Kilometer Array (SKA).

• *Pulsar Timing:* Long-term measurements of the time-of-arrivals of light pulses from arrays of pulsars can be used to provide some of the most sensitive probes of substructure at small scales. Dark matter clumps moving around the Earth-pulsar system imprint characteristic shapes in the timing residuals measured by pulsar timing arrays and can be used to search for small scale structure in the galaxy by their gravitational influence alone[3,11,16,26,40–43]. Clumps passing close by to the Earth or pulsar accelerate the astrophysical body, resulting in a Doppler shift in the pulsar frequency. Additionally, if the clump passes through the line of sight it will cause a Shapiro time delay in the signal. This technique is sensitive not only to very compact objects such as black holes, but also to more diffuse objects such as DM minihalos[3,11,16,40].

Pulsar timing observatories such as the Square Kilometer Array have been shown to be sensitive to DM substructure across a wide range of masses above $\sim 10^{-11} M_\odot$[16,40]. In addition to single transits, pulsar timing data can be searched for a stochastic background from distributions of DM substructure at low masses, extending the sensitivity of these probes to $\gtrsim 10^{-13} M_\odot$ and to halo densities as low as predicted by cold dark matter[40]. In addition to pulsar timing, upcoming stellar radial velocity surveys with measurement precision of $\sim 10\,\mathrm{cm/s}$ should also have sensitivity to accelerations induced by planet-mass-scale halos[10].

• *Lensing of Gravitational Waves:* Observations of gravitationally lensed distant quasars and galaxies have a long history of probing the invisible dark matter mass throughout the Universe, with high-resolution imaging of galaxy-scale lenses closing in on the $10^6 - 10^7 M_\odot$ scale. The recent advent of gravitational wave astronomy has the potential to push down the sensitivity to small dark matter halos by several orders of magnitude[15,38]. Indeed, strongly lensed binary black hole (BBH) merger events detectable in the current LIGO band have periods similar to the Schwarzschild timescale of $\sim 10^2 - 10^3 M_\odot$ compact dark matter clumps. This coincidence of scales leads to a distinctive gravitational wave diffraction pattern that is imprinted on the waveform of the gravitational wave signal. Since the lensing cross section increases significantly with larger source redshift, third generation gravitational wave detectors capable of detecting BBH mergers out to $z_\mathrm{s} \sim 2-4$ offer the most promising path forward for this technique. Lensed fast radio bursts are expected to be sensitive to low-mass structures via similar diffractive effects[27,30,33].

The Path Forward

We advocate for enhanced theoretical, instrumentation, and data analysis efforts to develop experimental techniques to access stellar- and planet-mass-scale extended dark matter structures. To enable the success of these experiments, it is *essential for the community to support dedicated theory and simulation efforts*, both (1) to model the matter distribution and observables at extremely small scales, and (2) to differentiate between various dark matter and early universe physics models using detailed and diverse sets of observations. At this stage, we recommend that multiple experimental approaches be explored in parallel to better quantify their sensitivity, robustness, and long-term potential, and to check for consistency between signals.

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